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DEVELOPMENT OF HIGH RESOLUTION EDDY CURRENT IMAGING USING AN ELECTRO-MECHANICAL SENSOR (POSTPRINT)

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14. ABSTRACT
Typical eddy current probes are based on measuring the impedance change of a coil excited by an AC current when the coil is placed above a conductive sample. These types of probes are limited in spatial resolution to the dimensions of the coil, and coil diameter is limited by operating frequency. Because of this, the highest resolution available with these probes is on the order of 100 um. While detecting the impedance change of the probe has limited special resolution, various methods of detecting the change in magnetic field in and around the coil have been shown to improve the resolution of a standard coil. These methods have improved the resolution in eddy current imaging to 25 nm. To date, the resolutions achievable by modern eddy current technology have failed to encompass the 100nm – 100 um range, which would be ideal for microstructure characterization of conductive materials. In this paper, a new probe, called the electro-mechanical eddy current sensor (EMECS), is presented that is based on the electromechanical design to fill this resolution gap. The new probe is designed and developed with a sharpened magnetic tip attached to the membrane of an electret microphone. The magnet is actuated by an external coil with a low current AC voltage. The motion of the magnet produces eddy currents in a conductive sample, which then result in a damping force on the magnet. The results of the experimental measurements demonstrate that this probe has spatial resolution that is much higher compared with the measurements using the external excitation coil only. The role of competing eddy currents produced by the motion of the magnet and the excitation coil in the material are examined with numerical analysis and the effects of the eddy currents from the excitation coil are shown to be negligible. A governing equation for the probe is presented that treats the magnet as a magnetic dipole and uses the eddy current forces as a damping term in the equation of motion for the membrane. The equation is solved with finite differences and the resolution is indeed shown to be on the order of the tip diameter.

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DEVELOPMENT OF HIGH RESOLUTION EDDY CURRENT IMAGING USING AN ELECTRO-MECHANICAL SENSOR

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ABSTRACT. Typical eddy current probes are based on measuring the impedance change of a coil excited by an AC current when the coil is placed above a conductive sample. These types of probes are limited in spatial resolution to the dimensions of the coil, and coil diameter is limited by operating frequency. Because of this, the highest resolution available with these probes is on the order of 100 um. While detecting the impedance change of the probe has limited special resolution, various methods of detecting the change in magnetic field in and around the coil have been shown to improve the resolution of a standard coil. These methods have improved the resolution in eddy current imaging to 25 nm. To date, the resolutions achievable by modern eddy current technology have failed to encompass the 100nm – 100 um range, which would be ideal for microstructure characterization of conductive materials. In this paper, a new probe, called the electro-mechanical eddy current sensor (EMECS), is presented that is based on the electromechanical design to fill this resolution gap. The new probe is designed and developed with a sharpened magnetic tip attached to the membrane of an electret microphone. The magnet is actuated by an external coil with a low current AC voltage. The motion of the magnet produces eddy currents in a conductive sample, which then result in a damping force on the magnet. The results of the experimental measurements demonstrate that this probe has spatial resolution that is much higher compared with the measurements using the external excitation coil only. The role of competing eddy currents produced by the motion of the magnet and the excitation coil in the material are examined with numerical analysis and the effects of the eddy currents from the excitation coil are shown to be negligible. A governing equation for the probe is presented that treats the magnet as a magnetic dipole and uses the eddy current forces as a damping term in the equation of motion for the membrane. The equation is solved with finite differences and the resolution is indeed shown to be on the order of the tip diameter.

INTRODUCTION

An oscillating current flowing thru a coil produces an oscillating magnetic field. When an electrically conducting material like a metal is brought close to the coil, the oscillating magnetic field produces eddy currents in the metallic material [1-3]. The strength of the eddy current depends on the electrical conductivity of the material, the distance between the coil and the material and the frequency of the excitation of the coil. The eddy currents penetrate into the material and their strength decays exponentially. The

penetration depth or "skin depth" depends on the frequency and the electrical conductivity. At very high frequencies the skin depth becomes very small and will be close to the surface of the sample.

The eddy currents in the electrical conductor produce a magnetic field opposing the magnetic field generated by the coil. The electrical impedance of the coil, placed in close proximity to a metal is altered due to the eddy currents in the metal. Measurement of the change in the impedance is a method to determine the electrical conductivity of the metal. If the metallic material is magnetic, then impedance measurements can be used for determination of electrical and magnetic properties of the metal. Since the coil does not have to contact the surface of the material, eddy current has become a standard tool for detecting non-contact electrical and magnetic properties. The presence of a defect or crack under the electromagnetic coil dramatically changes the electrical impedance compared with the same material without a defect. Measurement of the difference between the two impedances has become the basis of the development of eddy current nondestructive evaluation of electrically conductive materials. It is possible to produce an image of the local electrical conductivity and magnetic property variations by mapping the impedance data acquired from scans of a conductive sample. The spatial resolution of the eddy current images depends on the diameter of the coil and the spreading of the magnetic field. Sensitivity issues at smaller coil diameters have limited the resolution to the range of 100 to 200µm [4].

Other methods of eddy current measurements have been developed in the past decade. Most often this is achieved by generating eddy currents using a coil and detecting the magnetic field using sensors like Hall Effect (HE) [5-7], Magneto-Resistance (MR) and Giant Magneto-Resistance (GMR) [8-10] sensors, Flux Gate sensors [11,12], SQUID sensors [13,14] etc. In all these methods, large electromagnetic coils are used to generate eddy currents in the material and the sensors are scanned across to detect the magnetic field due to eddy currents. The spatial resolution in each of the techniques is limited by the dimension of the sensors. Since the micro-magnetic field sensors are highly sensitive to static magnetic fields, they are often limited to low frequency measurements and imaging.

To improve the spatial resolution beyond the coil diameter, modifications to the atomic force microscope (AFM) were developed in the last decade. Hoffman et al. [15] used magnetic force microscope [MFM] to generate and detect eddy currents. A magnetic tip cantilever of a MFM equipped with a piezoelectric element was brought close to an electrical conductor and was vibrated. A vibrating magnetic tip generates eddy currents in the material under the tip. The magnetic field of the eddy currents in the material opposes the motion of the magnetic tip causing damping of the cantilever. Changes in the amplitude of the motion of the cantilever is measured and mapped to obtain an eddy current image of the sample. The spatial resolution of the eddy current images produced using MFM is slightly lower than the tip diameter of 20-30 nm. The sensitivity of the method depends on the magnetic field strength of the tip and spring constant of the cantilever. Lantz et al. [16] used a stronger, larger diameter magnet to increase the sensitivity of eddy current imaging. The cantilever used in these experiments had spring constants similar to experiments of Hoffman etal [15]. This use of a stronger magnet led to higher sensitivity while the larger diameter reduced the spatial resolution. To preserve high sensitivity and high spatial resolution Vijay et al. [17] used a low spring constant cantilever with sharp magnetic tip, and separated the generation and detection of eddy currents. A small coil was placed under the sample was used for eddy current generation while a low spring constant cantilever with magnetic tip was used for detection. While high sensitivity and high resolution was achieved, the instrument operates in the through-
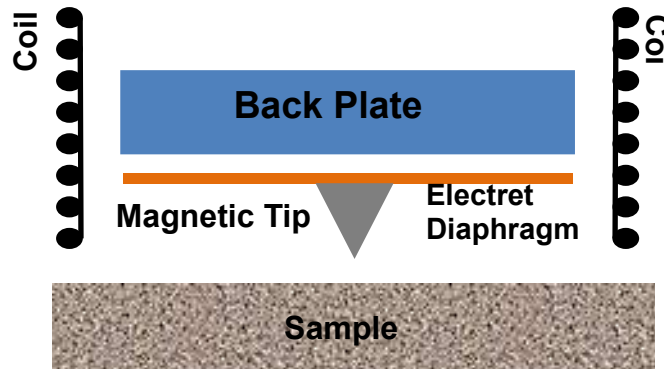
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FIGURE 1. Schematic of the new probe design.

transmission mode. Developing an instrument with high spatial resolution and high sensitivity is challenging.

While eddy current imaging can be performed with low macroscopic resolution with electromagnetic coils, extremely high resolution in the tens of nanometers range, has been achieved with modified AFM. This leaves a significantly large gap of spatial resolution of hundreds of nanometers to hundreds of micrometers. Furthermore, high resolution requires sophisticated instrumentation like an AFM. In this work, a new probe design based on the MFM is presented and is shown to be a promising method to bridge this gap.

PROBE DESIGN

Figure 1 shows the design of the new Electo-Mechanical Eddy Current System (EMECS) probe. Similar to the MFM, the design relies on time varying magnetic fields produced by the moving magnet that create eddy currents in a conductive sample. These currents create opposing magnetic fields that damp the motion of the magnet. It is expected that the spatial resolution of the probe will be on the order of the diameter of the magnetic tip. In this probe design the magnet is attached to the membrane of an electret microphone. A large coil is used as an external excitation coil which moves the magnet. The motion of the magnet is detected as the output of the microphone (Fig 2), and changes in the amplitude correspond to changes in the magnetic field at the magnet. The membrane and back plate are connected to a local pre-amp which greatly increases the signal to noise ratio. A lock-in amplifier was used to measure the DC values of amplitude change. This allowed for very fine bit resolution in the amplitude range of interest. In addition, the lock-in amplifier allows characterization of the phase change along with the amplitude change. Though the phase measurements were not collected for this study, changes in the phase are expected to vary with changes in the damping force.

TEST CASE

A probe based on this design was constructed. The actual probe built for this study is shown in Fig 3. The dimensions are given in Table 1. As an initial study, the magnet was chosen to have cylindrical geometry due to availability and cost. The magnet could be sharpened to enhance resolution later, but was not done for this proof of concept study. As is noted in the table, the magnetic fields from the magnet were much higher than those
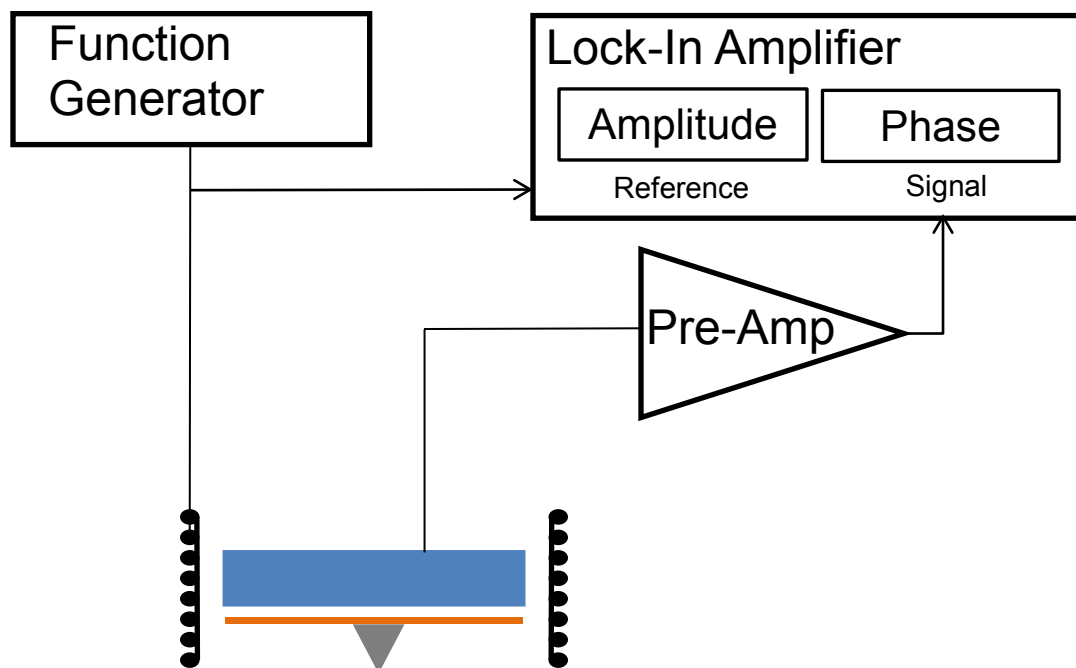
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FIGURE 2. Schematic of the measurement system used for the EMECS.

FIGURE 3. Image of the assembled probe. The black external housing is the coil and the microphone is secured in the middle of the coil. The magnet shown here is a cylindrical magnet.

seen in the middle of the coil at the operating frequency of 1 kHz. This, along with model validation presented in a later section, show that the effects of the external magnetic field are negligible compared to the large magnetic fields in the vicinity of the magnetic tip. To prove the concept, the coil was used as a traditional eddy current probe by measuring the impedance change as it is run over a large EDM notch. The EMECS was then constructed with the same coil and run over the same notch. From this data, the width at half max (WAHM) resolution of both methods were compared.

RESULTS

The results from the initial measurements are shown in Fig 4. The width at half max for the ECEMS was 4.56 mm which was well below the WAHM for the coil alone

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TABLE 1. Dimensions of the magnetic tip and coil used for this study.

Magnetic Tip Parameters	
Diameter	1.5 mm
Height	1.5 mm
Mag. Field (@ Tip)	2.6 kG

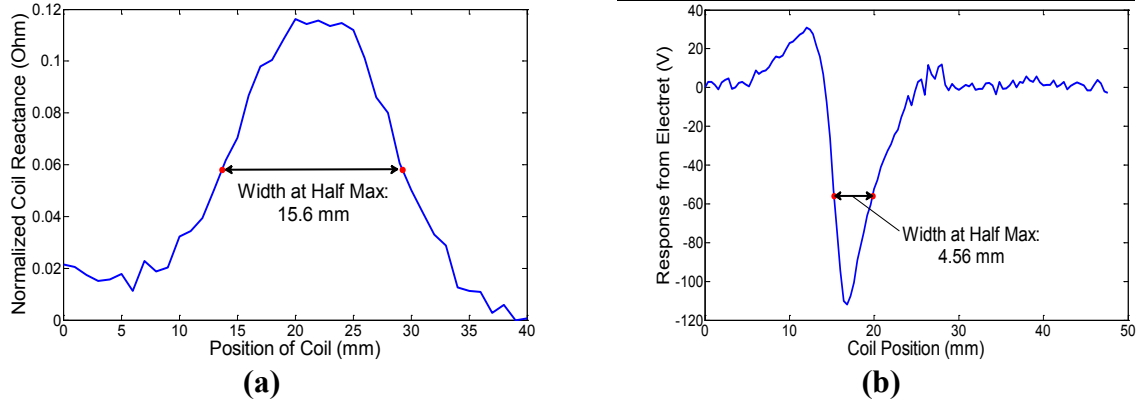| Coil Parameters	
In. Diam	11.4 mm
Out Diam	28 mm
Height	30 mm
Mag. Field (In Center @ 1 kHz)	3.3 G

(a)

(b)

FIGURE 4. (a) An image of the coil reactance change when the coil was run over the notch, and (b) an image of the same scan with the EMECS.

(15.6 mm) and below the diameter of the coil. This shows that the ECEMS at least improved the resolution of the coil. The resolution was not on the order of the diameter of the magnet, as expected, but possible reasons and remedies for this and the asymmetries in the data are explained in the discussion section.

MODELS

Several numerical models were used for validation of different portions of the study. A finite element model of the coil alone was developed to verify that magnetic field measurements in the middle of the coil were in agreement to theory. Predicted magnetic field values from theory were 2.8G while the field was measured at 3.3G, which validates that the field estimates are at least in the correct range. An expression for the damping force on a moving magnetic dipole was derived in Hoffman et al. [15] and is shown in equation 1.

$$F_d = -\frac{\sigma\mu^2 m^2}{64\pi d^3}\frac{\partial d}{\partial t}e_z \tag{1}$$

In this expression, σ and μ are the conductivity and permeability of the sample, respectively, m is the magnetization of the magnet, d is the total distance from the sample to the magnetic dipole location, and e_z is a unit vector in the perpendicular direction to the sample surface. The damping force clearly relies heavily on the liftoff of the probe. To determine the magnetization of the magnet used in this test, the magnet was also modeled with finite elements, but in a magneto-static sense. The field at the end of the magnet was measured with a gauss meter and this data was used in conjunction with the numerical model to determine the magnetization of the magnet by minimization of squared residuals. Once the parameters of equation 1 are known, the force term can be used in conjunction with the equation of motion of the membrane to give the full equation of motion for the

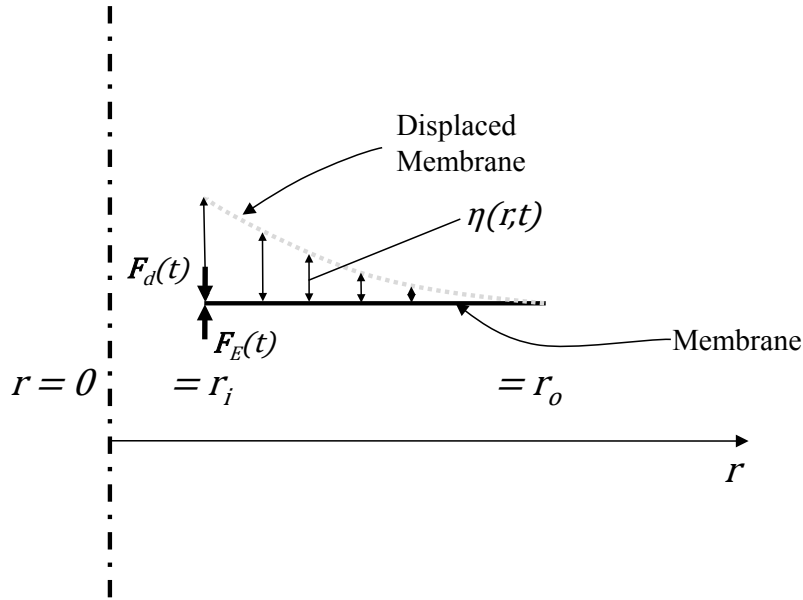Distribution A. Approved for public release; distribution unlimited.

FIGURE 5. Axi-symmetric geometry of the membrane vibration problem.

system (2). In this equation, ρ is the mass density per unit area, T is the tenstion applied to the membrane per unit length, and $\boldsymbol{\eta}$ is the displacement of the membrane. r_i is the radius of the magnet, and r_o is the radius of the membrane. The 2-D, axially-symmetric geometry

$$\rho \frac{\partial^2 \eta}{\partial t^2} - T\nabla^2 \boldsymbol{\eta} = 0, \quad r_i < r < r_o \tag{2}$$

of the problem is shown in figure 5. In this diagram, the force $\boldsymbol{F}_E$ acting on the boundary is the magnetic excitation force on the magnet and $\boldsymbol{F}_d$ is the damping force due to the eddy currents generated in the specimen. With the appropriate boundary conditions, the solution of this problem could yield a straightforward approach at determining material parameters in the damping force term given an experimentally determined decrease in the amplitude of vibration. These measurements are left for future work at this point.

MICROPHONE SENSITIVITY

To determine whether the microphone would be sensitive enough to detect the amplitude of the change of vibration in the membrane due to the damping force, equation (1) was used in conjunction with the results of the inversion method for determining the magnet characteristics. The total displacements of the magnet were measured by exciting the magnet with the external coil and measuring the displacements with a laser vibrometer. Displacement was estimated to be at 8.2 nm in magnitude. These values were plugged into equation (1) assuming harmonic excitation, along with the material constants for several different materials to give a rough estimate of the damping forces that would be measured by the microphone. The results from this are given in Table 2, along with the corresponding pressures on the membrane. It is assumed that the membrane was designed for use in the audio frequency and pressure range which has a minimum of 20 µPa at 1kHz. The numbers calculated for the different material shown indicate that a sensitive electret microphone could detect the pressures seen in this eddy current problem.

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TABLE 2. Damping forces and pressures resulting from various materials at 1 kHz excitation frequency

Material (Conductivity)	Eddy Current Damping Force	Pressure on Diaphragm
Aluminum 7075 T6 (1.92e7 S/m)	110 nN	62 mPa
Copper Annealed (5.69e7 S/m)	325 nN	185 mPa
Ti-6Al-4V (5.61e5 S/m)	3.2 nN	2 mPa

DISCUSSION

The preliminary results from the experiments seem to show an increase in spatial resolution, but there are some issues in the plots that should be discussed. First of all, as stated in the design section, the expected resolution of the probe is on the order of the diameter of the magnet, whereas the actual resolution appears to be greater than 3X this resolution. When designing the probe, it was assumed that the magnetic field was parallel to the velocity of the magnet, and the Lorentz force term, $F = qv \times B$, would be zero. This assumption is not necessarily true, however, due to eddy current generation in the sample from the external excitation coil. In an unflawed specimen, this term should still be zero, but the presence of the flaw would create magnetic field components that are perpendicular to the velocity of the magnet which would result in seeing the notch much further out than expected. Also, the asymmetries in the data can be explained by this, and the fact that the magnet is not exactly in the center of the probe, nor is it a perfect dipole. The reason this did not affect the MFM designs is the coil used to excite the MFM magnet was on the opposite side of the sample.

CONCLUSION

A gap in possible resolution range for eddy current measurements makes ECT evaluation of microstructure features in metallic structures difficult. To address this gap, a new sensor design, based on the concepts from MFM, was created which relies on the geometric properties of a magnetic particle to improve resolution. Preliminary experimental and modeling results seem to indicate that this probe will offer the desired resolution improvement over a standard ECT probe.

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